Analysis of ASME Boiler, Pressure Vessel, and Nuclear Components in the Creep Range

Second Edition

Maan H. Jawad and Robert I. Jetter

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In memory of
Betty Jetter
1940–2020

Contents

Preface

Many structures in chemical plants, refineries, and power generation plants operate at elevated temperatures where creep and rupture are a design consideration. At such elevated temperatures, the material tends to undergo gradual strain with time, which could eventually lead to failure. Thus, the design of such components must take into consideration the creep and rupture of the material. In this book a brief introduction to the general principles of design at elevated temperatures is given with extensive references cited for further in-depth understanding of the subject. A key feature of the book is the use of numerous examples to illustrate the practical application of the design and analysis methods presented.

This book is divided into nine chapters. The first chapter is an introduction to various creep topics such as allowable stresses, creep properties, elastic analog, and reference stress methods, as well as a few introductory topics needed in various subsequent chapters.

Structural members in the creep range are covered in Chapters 2 and 3. In Chapter 2, the subject of structural tension members is presented. Such members are encountered in pressure vessels as hangers, tray supports, braces, and other miscellaneous components. Chapter 3 covers beams and plates in bending. Components such as piping loops, tray support beams, internal piping, nozzle covers, and flat heads are included. A brief discussion of the requirements of ANSI B31.1 and B31.3 in the creep regime is given.

Chapters 4 and 5 discuss stress analysis of shells in the creep range. In Chapter 4, various stress categories are defined and an analysis of various components using "load-controlled limits," as defined in ASME VIII-2, is discussed. Comparisons are also given between the design criteria in ASME VIII-2 and ASME III-5 and the limitations encountered in ASME VIII-2 when designing in the creep range. Chapter 5 covers the analysis of pressure components using "strain and deformation-controlled limits." Discussion includes the requirements and limitation of the "A Test" and "B Test" outlined in ASME VIII-2.

Cyclic loading in the creep-fatigue regime, using the “Strain Method,” is discussed in Chapter 6. Both repetitive and non-repetitive cycles are presented with some examples illustrating the applicability and intent of ASME VIII-2 in non-nuclear applications.

Chapter 7 gives a brief presentation of creep fatigue analysis using the “Remaining Life Method” outlined in the API 759/ASME FFS-1 code. A comparison of the results obtained from this method, versus the results obtained from the “Strain Method,” is made.

Chapter 8 outlines the requirements for creep analysis in nuclear components given in ASME III-5. Some of the differences between these requirements and those of ASME VIII-2 Creep Rules are presented.

Compressive stress in components is discussed in Chapter 9. External pressure charts obtained from isochronous curves, as well as from the Remaining Life method, are presented. Cylindrical and spherical shells, as well as axial structural members, are discussed. Simplified methods are presented for design purposes. The assumptions and limitations required to derive the simplified methods are also given.

The book also includes six appendices. Appendix A lists ASME VIII-2 supplemental creep rules, as shown in ASME Code Case 2843. Appendix B lists the equations for constructing the Isochronous Stress-Strain Curves presently used in ASME. Appendix C shows some equations for the tangent modulus, Et. Appendix D outlines the derivation of the Bree diagram in ASME. Appendix E gives some constants used in the remaining life methods, and Appendix F gives some conversion factors.

The rules for creep analysis of pressure vessels in ASME VIII-2 are presently in ASME Code Case 2843. These rules are a simplification of the rules in the nuclear code, ASME III-5, which are more extensive since they cover broader applications such as piping and valves. The rules of Code case 2843 are intended to be placed in the body of ASME VIII-2. In doing so, the paragraph numbers, as well as the table and figure numbers, will change. In order to keep the discussion of the topics in this book consistent with Code Case 2843, a copy of the code case is shown in Appendix A of this book. In order to avoid confusion, reference in this book is made to ASME VIII-2 supplemental creep rules to indicate creep rules presently in Code Case 2843 that will eventually be incorporated in ASME VIII-2. The equations in Chapter 9 for external pressure are taken, in part, from ASME Code Case 2964, that will eventually be incorporated in ASME VIII as well.

Frequently referenced ASME standards in this book are abbreviated for simplicity. ASME Section I is abbreviated as ASME I, ASME Section VIII, Division 1 is abbreviated as ASME VIII-1 and ASME Section VIII, Division 2 is abbreviated as ASME VIII-2. Similarly, ASME Section III, Division 5 is abbreviated as ASME III-5.

The units expressed in this book are mainly in the customary English units such as oF, ksi, inches, and lbs. Equivalent SI units are also shown, such as oC, MPa, mm, and kgs. Example problems are solved in either customary or SI units.

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Abbreviations for Organizations

AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
API	American Petroleum Institute
ASM	American Society of Metals
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BS	British Standard
EN	European Standard
IBC	International Building Code
MPC	Materials Properties Council
WRC	Welding Research Council

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Basic Concepts

OPERATING UNIT IN A REFINERY

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1.1 Introduction

Many vessels and equipment components encounter elevated temperatures during their operation. Such exposure to elevated temperature could result in a slow continuous deformation and creep of the equipment material under sustained loads. Examples of such equipment include hydrocrackers at refineries, power boiler components at electric generating plants, turbine blades in engines, and components in nuclear plants. The temperature at which creep becomes significant is a function of material composition and load magnitude and duration.

Components under loading are usually stressed in tension, compression, bending, torsion, or a combination of such modes. Most design codes provide allowable stress values at room temperature or at temperatures well below the creep range; for example, the codes for civil structures such as the American Institute of Steel Construction and International Building Code. Pressure vessel codes such as the ASME Boiler and Pressure Vessel Code, British, and the European Standard BS EN 13445 contain sections that cover temperatures from the cryogenic range to much higher temperatures where effects of creep are the dominant failure mode. For temperatures and loading conditions in the creep regime, the designer must rely on either in-house criteria or use a pressure vessel code that covers the temperature range of interest. Table 1.1 gives a general perspective on when creep becomes a design consideration for various materials. It is broadly based on the temperature at which creep properties begin to govern allowable stress values in the ASME Boiler and Pressure Vessel Code. There may

Table 1.1 Approximate temperatures[1] at which creep becomes a design consideration in various materials.

	Temperature	
Material	**°F**	**°C**
Carbon and low alloy steel	700–900	370–480
Stainless steels	800–1000	425–535
Aluminum alloys	300	150
Copper alloys	300	150
Nickel alloys	900–1100	480–595
Titanium and zirconium alloys	600–650	315–345
Lead	Room temperature	

[1] These temperatures may vary significantly for the specific product chemistry and failure mode under consideration.

be other specific considerations for a particular design situation, e.g., a short duration load at a temperature above the threshold values shown in Table 1.1. These considerations will be discussed later in this chapter in more detail.

It will be assumed in this book that material properties are not degraded due to process conditions. Such degradation can have a significant effect on creep and rupture properties. Items such as exfoliation Thielsch (1977), hydrogen sulfide Dillon (2000), hydrogen embrittlement, nuclear radiation, and other environment impacts may have great influence on the creep rupture of an alloy; engineers have to rely on experience and field data to supplement theoretical analysis.

One of the concerns for design engineers is the recent increase in allowable stress values in both ASME VIII-1 and VIII-2 and their effect on equipment design, such as hydrotreaters. The recent increase in allowable stress reduces the temperature at which creep controls and upgrading older equipment based on the newer allowable stress requires the knowledge of creep design covered in this book.

1.2 Creep in Metals

1.2.1 Description and Measurement

Creep is the continuous, time-dependent deformation of a material at a given temperature and applied load. Although, conceptually, creep will occur at any stress level and temperature if the measurements are taken over very long periods, there are practical measures of when creep becomes significant for engineering considerations in metallic structures.

Metallurgically, creep is associated with the generation and movement of dislocations, cavities, grain boundary sliding, and mass transport by diffusion. There are many studies of these phenomena and there is extensive literature on the subject. Fortunately for the practicing engineer, a detailed mastery of the metallurgical aspects of creep is not required to design reliable structures and components at elevated temperature. What is required is a basic understanding of how creep is characterized and how creep behavior is translated into design rules for components operating at elevated temperatures.

A creep curve at a given temperature is experimentally obtained by loading a specimen at a given stress level and measuring the strain as a function of time until rupture. Figure 1.1 conceptually shows a standard creep testing machine. A constant force is applied to the specimen through a lever and deadweight load. Typically, the test specimen is surrounded by an electrically controlled furnace. Because creep is highly temperature-dependent, considerable care must be taken to ensure that the specimen temperature is maintained at a constant value, both spatially and temporally.

There are various methods for measuring strain. Figure 1.2 shows one such arrangement suitable for higher temperatures and longer times, which uses